SECTION 7.0
EMPLACEMENT TECHNIQUES FOR PERMEABLE BARRIER INSTALLATION

Once the desired location, configuration, and dimensions of the permeable barrier have been determined, a suitable emplacement technique has to be selected. Conventional and innovative techniques that could be used to install a permeable barrier are discussed in detail below and are summarized in Table 7-1. Factors that limit and ultimately decide the type of emplacement method used include:

- Depth of emplacement
- Required reactive cell permeability
- Site topography
- Site access and work space
- Geotechnical constraints
- Soil characteristics (of backfill)
- Disposal requirements of contaminated trench spoils
- Costs.

7.1 COMMERCIALLY AVAILABLE TECHNIQUES FOR REACTIVE CELL EMPLACEMENT

The reactive cell is the portion of the aquifer that is modified to contain the reactive medium through which a contaminated plume will flow. Figure 7-1 shows various arrangements of the reactive cell that may be used depending on site-specific hydrogeologic conditions. In a continuous reactive barrier configuration, the reactive cell runs along the entire width of the barrier. In a funnel-and-gate system, only a portion of the total barrier width is taken up by the reactive cell. In some reactive cells, particularly when the surrounding aquifer is heterogeneous, the reactive medium may be bounded on both upgradient and downgradient sides by thinner sections of pea gravel. The pea gravel serves to increase the hydraulic conductivity surrounding the reactive medium and uniformly draw groundwater flow into the reactive cell through a homogeneous material. The pea gravel also provides a homogeneous setting for monitoring the influent to and effluent from the reactive cell.

The reactive cell is generally completed to approximately 2 feet above the water table to allow for water-level fluctuations and medium minimization, although this may vary from site to site. Generally, the reactive cell is keyed in about 1 foot into the aquitard. In a funnel-and-gate system, the funnel walls are generally keyed in about 5 feet into the aquitard. If the continuity or integrity of the aquitard is questionable, a geotextile fabric or a concrete floor placed at the base of the reactive cell helps prevent any contamination from entering the reactive cell through underflow. Monitoring well clusters can be installed during cell construction within the reactive medium or in the upgradient and downgradient pea gravel.

Four emplacement techniques are discussed in Sections 7.1.1 through 7.1.4: conventional trench excavation, caisson-based emplacement, mandrel-based emplacement, and continuous trenching. All four have been used at previous sites for reactive cell emplacement. Trench excavation has been widely used at previous sites. However, other techniques such as caisson emplacement are being used increasingly as deeper plumes are targeted.

Table 7-1. Summary Table of Various Techniques for Barrier Emplacement

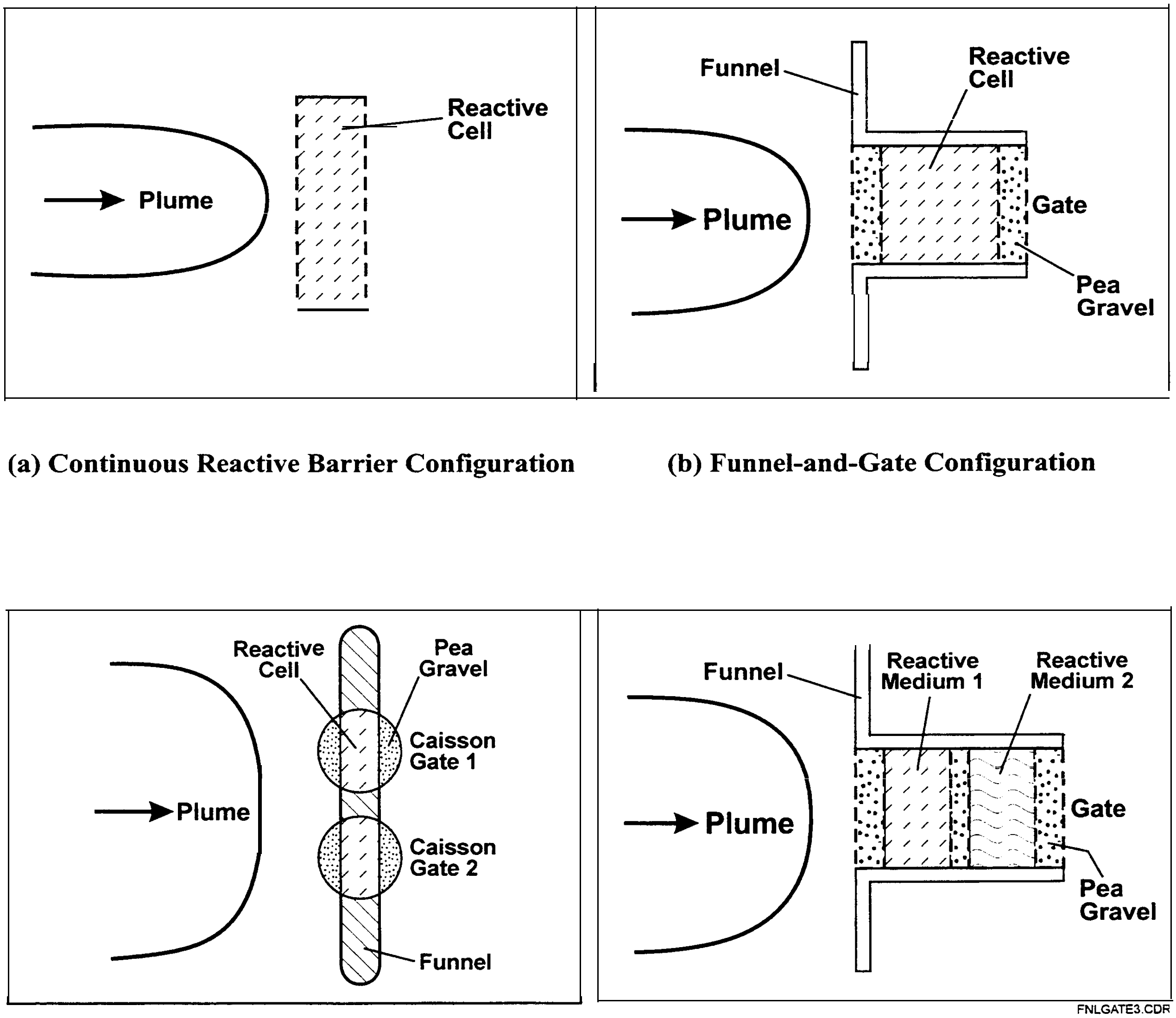
Emplacement Techniques	Maximum Depth (Ft)	Vendor-Quoted Cost	Comments
IMPERMEABLE BARRIER TECHNIQUES			
Soil-Bentonite Slurry Wall • By Standard Backhoe Excavation • By Modified Backhoe Excavation • By Clamshell Excavation	 30 80 150	 $2-8 /ft^2$ $2-8 /ft^2$ $6-15 /ft^2$	Requires a large working area to allow for mixing of backfill. Generates some trench spoil. Relatively inexpensive when a backhoe is used.
Cement-Bentonite Slurry Wall • By Standard Backhoe Excavation • By Modified Backhoe Excavation • By Clamshell Excavation	 30 80 200	 $4-20 /ft^2$ $4-20 /ft^2$ $16-50 /ft^2$	Generates large quantities of trench spoil. More expensive than other slurry walls.
Composite Slurry Wall HDPE Geomembrane Barrier	100+ 40-50	NA $35 /ft^2$	Multiple-barrier wall. Permeability less than 1×10^{-7}
Steel Sheet Piles Sealable-Joint Piles	60 60	$17-65 /ft^2$ $15-25 /ft^2$	No spoils produced. Groutable joints
PERMEABLE OR IMPERMEABLE BARRIER TECHNIQUES			
Caisson-Based Emplacement	45+	NA	Does not require personnel entry into excavation; relatively inexpensive.
Mandrel-Based Emplacement	190	$7 /ft^2$	Relatively inexpensive and fast production rate. Multiple void spaces constitute a reactive cell.
Continuous Trenching	35-40	$5-12/ft^2$	High production rate. High mobilization cost.
Jetting	200	$40-200 /ft^2$	Ability to install barrier around existing buried utilities.
Deep Soil Mixing	150	$80-200 /yd^3$	May not be cost effective for permeable barriers. Columns are 3 to 5 feet in diameter.
Hydraulic Fracturing	80-120	$2300 per fracture	Can be emplaced at deep sites. Fractures are only up to 3 inches thick.
Jetting Saw Beam	50	$3-4 /ft^2$	Used for impermeable barriers.
Vibratory Beam	100	$7 /ft^2$	Driven beam is only 6 inches wide.

HDPE is high-density polyethylene.

7.1.1 Conventional Trench Excavation

Depending on the design of the permeable barrier, installation of the reactive cell may require the excavation of a trench that will house the reactive medium. Backhoes and clamshells are the most common types of equipment used for conventional trench excavation.

To ensure trench wall stabilization during cell construction, several techniques are used. Temporary steel sheet piles can be driven into the ground around the perimeter of the intended reactive cell prior to excavation, then reinforced with bracings. Sheet piling can also be used to temporarily separate



(a) Continuous Reactive Barrier Configuration

(b) Funnel-and-Gate Configuration

(c) Multiple Caisson Gates

(d) Serial Reactive Medium

Figure 7-1. Various Permeable Barrier Configurations

the reactive medium and pea gravel sections within the reactive cell (Figure 7-2). Dewatering of the trench may be required if high water tables are present and sheet piling cannot prevent groundwater seepage into the reactive cell. Another option involves excavation under the head of a biopolymer slurry (Owaidat, 1996). The slurry, which is composed of powdered guar bean, acts to maintain the integrity of the trench walls during installation of the cell. The guar gum will later biodegrade to mostly water after wall completion, and will have minimal effect on the permeability of the trench walls. A third method of trench stabilization involves the use of a trench box to create void space during the installation of either impermeable or permeable material (Breaux, 1996). However, the drawbacks to this method are that a trench has to be completely excavated before the box can be installed and temporary sheet piles must be used to maintain trench stability.

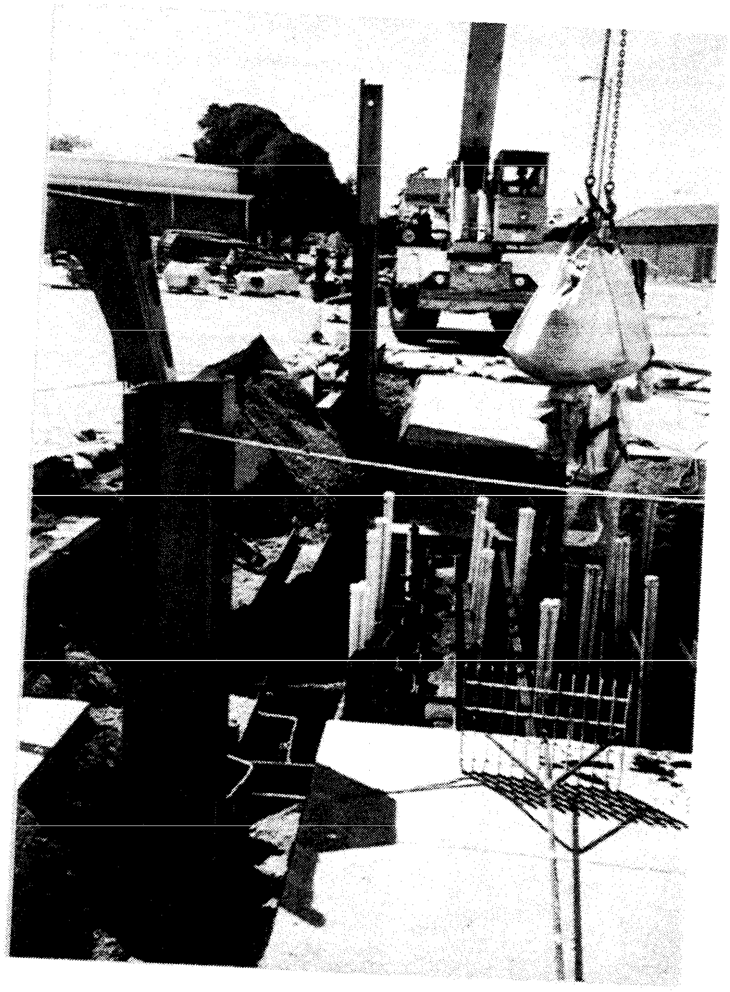


Figure 7-2. Emplacement of Reactive Iron Media (Suspended Bag) and Pea Gravel (Front-End Loader) into Divided Sections of a Permeable Cell (Courtesy of NFESC and PRC, Inc., 1996)

7.1.1.1 Backhoes. The most conventional and popular excavation technique is the backhoe. Standard backhoe excavation for shallow trenches down to 30 feet deep is the cheapest and fastest method available. The digging apparatus is staged on a crawler-mounted vehicle and consists of a boom, a dipper stick with a mounted bucket, and either cables or hydraulic cylinders to control motion (Figure 7-3). Bucket widths generally range in sizes up to 5.6 feet. Because the vertical reach of a backhoe is governed by the length of the dipper stick, backhoes can be modified with extended dipper sticks and are capable of reaching depths up to 80 feet (Day, 1996). Even greater depths are possible if benches can be excavated in which the backhoe can be located, enabling the whole backhoe to sit below grade. This can, however, be time-consuming and require a large area to be excavated to reach the required depth.

7.1.1.2 Clamshells. Down to around 200 feet deep, a clamshell bucket can be used. A cable-suspended mechanical clamshell is a crane-operated grabbing tool that depends on gravity for accurate excavation and closure of the grab (Figure 7-4). Therefore, a heavier tool is beneficial.

Hydraulic clamshells can be equipped with a kelly bar to help guide and control the vertical line in addition to providing weight. The verticality of the excavation is controlled by the repeated cyclic

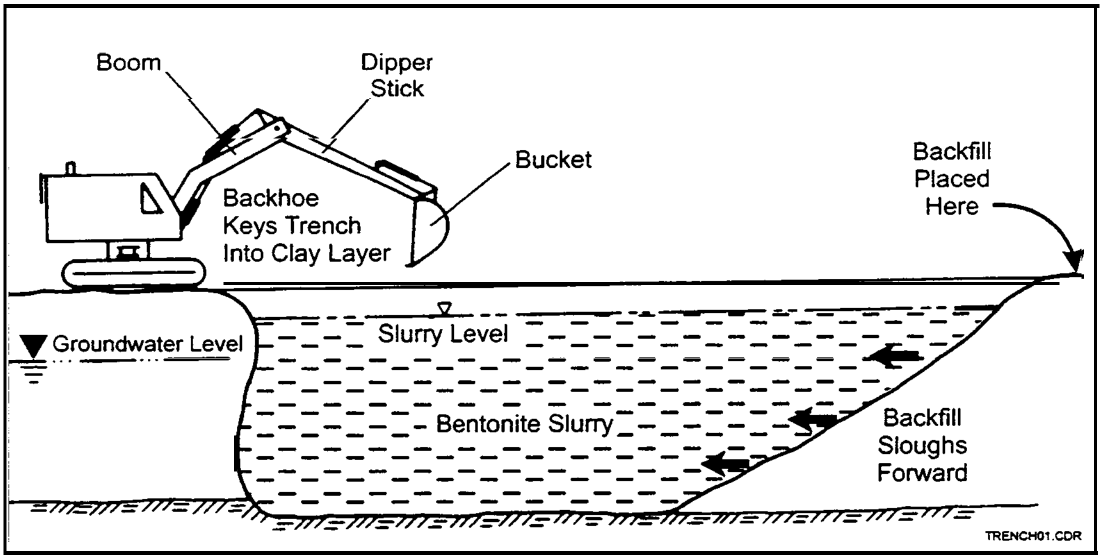


Figure 7-3. Conventional Backhoe Excavation of a Slurry Cutoff Wall (after Ryan, 1985)

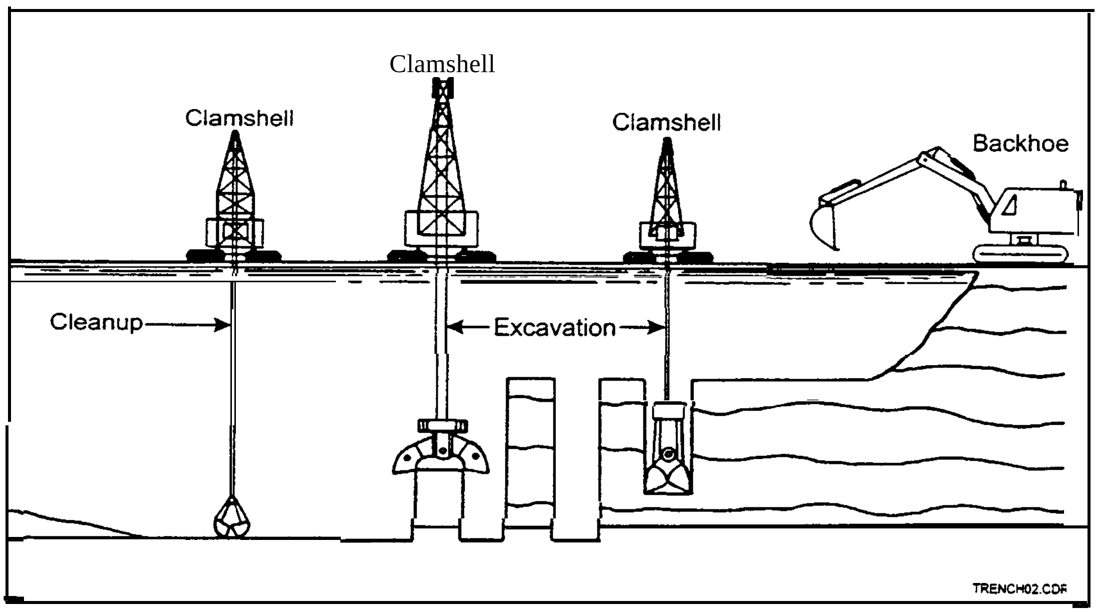


Figure 7-4. Trench Excavation Using a Clamshell and Backhoe (after Xanthakos, 1979)

lifting and lowering of the bucket under gravity. Mechanical clamshells are preferred over their hydraulic counterparts because they are more flexible in soils with boulders, can reach greater depths, and involve fewer maintenance costs. Clamshell excavation is popular because it is efficient for bulk excavations of almost any type of material except highly consolidated sediment and solid rock. It can also be controlled and operated in small and very confined areas as long as the boom can reach over the trench. Clamshell excavation, however, has a relatively low production rate compared to a backhoe. Also, worker safety can become an issue during clamshell excavation. At previous permeable barrier installations, construction sometimes involved sending a person into the trench to clear soil out of regions in the perimeter sheet piles that are not accessible to the clamshell.

7.1.2 Caisson-Based Emplacement

A caisson is a hollow, load-bearing enclosure generally used as a retaining method for excavations (Figure 7-5). Caissons can vary in size and shape depending on the applications for which they are intended. For the purpose of emplacing a reactive cell, a prefabricated, open, steel caisson can be used to temporarily facilitate excavation. Normally, an 8-foot-diameter (or smaller) caisson can be pushed or vibrated down into the subsurface. The smaller the diameter of the caisson, the more easily it can be driven in and maintained in a vertical position. Because caissons larger than 8 feet in diameter are not economical for reactive cell emplacement, the flowthrough thickness (and residence time in the reactive cell) is limited (see Figure E-10 in Appendix E for a caisson layout). Therefore, at sites with wide plumes, higher levels of contamination and higher groundwater velocity, funnel-and-gate systems with multiple caisson gates typically may be used to provide adequate residence time (see Figure 7-1 c).

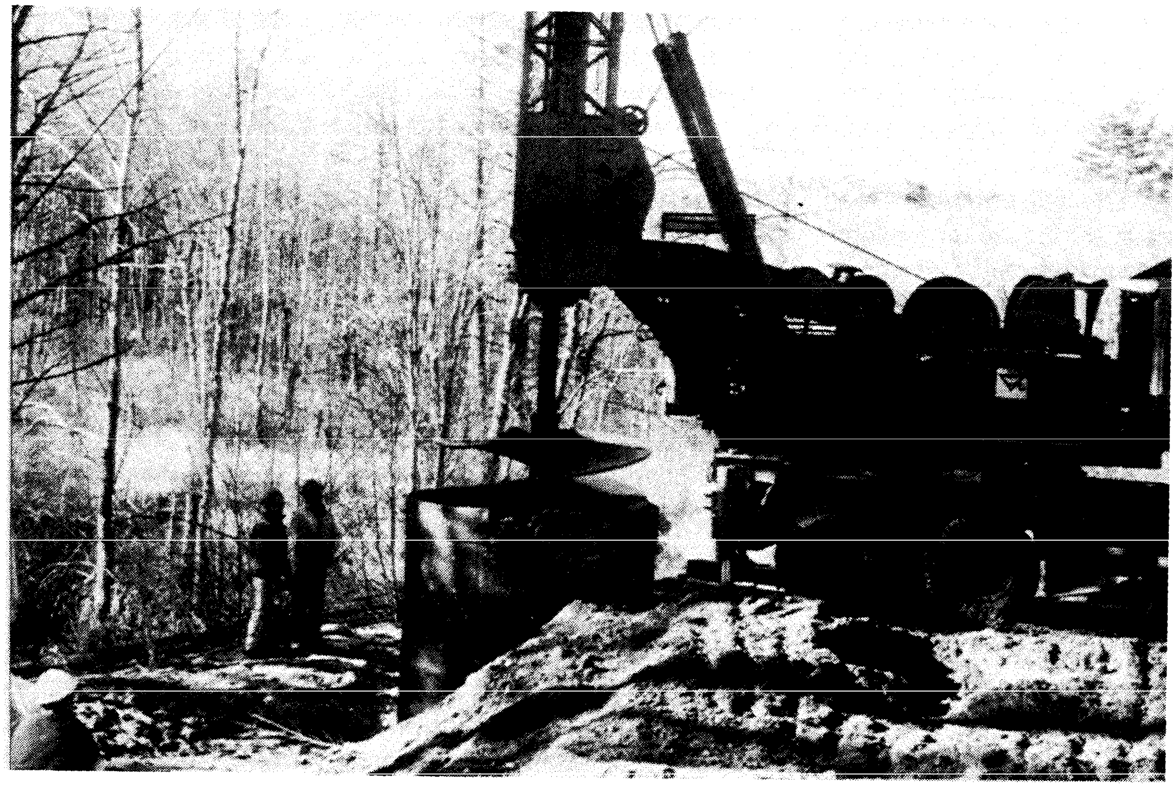


Figure 7-5. Emplaced Caisson Being Augered Out, Somersworth Sanitary Landfill, New Hampshire (ETI, 1997)

Once the caisson has reached the intended depth, the soil within the caisson can be augered out and replaced with a reactive medium. Upon completion of the reactive cell, the caisson can be pulled straight out. Because this method requires no internal bracings, the caisson can be installed from the ground surface and completed without requiring personnel to enter into the excavation. It can also be installed without having to dewater the excavation. Most small or large-sized reactive materials can be emplaced within the cell. Another advantage to this method is that it is inexpensive.

During emplacement of a caisson, some soil compaction can occur along the walls of the caisson that could lower the permeability around the intended reactive cell. If the formation contains a significant amount of cobbles, the caisson may be deflected to an off-vertical position as it is pushed down, or it may even meet refusal. At one previous installation, highly consolidated sediments and cobbles created difficulties in driving in and pulling out the caisson (ETI, 1996). It may also be difficult to drive a caisson to depths greater than about 45 feet. However, in the absence of such geotechnical difficulties, caissons have the potential to provide an inexpensive way to emplace a funnel-and-gate system and have been used for some recent permeable barrier installations (see Appendix E).

7.1.3 Mandrel-Based Emplacement

In this method, a hollow steel shaft, or mandrel, is used to create a vertical void space in the ground for the purpose of emplacing reactive media. A sacrificial drive shoe is placed over the bottom end of the mandrel prior to being hammered down through the subsurface using a vibratory hammer. Once the void space is created, it can then be filled with a reactive medium in one of two ways. One method uses a tremie tube to simply pour the media loosely down the hole. After a desired depth is reached, the mandrel is extracted, leaving the drive shoe and media. Another way to complete the cell is to emplace wick drains, geomembranes, or geofabrics in conjunction with reactive media.

Some disadvantages to this technique include the limited size of the reactive cell, which is controlled by the size of the mandrel, typically 2-inch x 5-inch. Therefore, a series of mandrel-emplaced voids would constitute a reactive cell rather than a single insertion. Because the mandrel is hammered down using a vibratory hammer, it is possible that subsurface obstructions during installation can cause the mandrel to deviate from an intended vertical path. Also, compaction can occur around the individual voids as the mandrel is driven down, lowering the permeability of the soil.

Mandrel-based emplacement does have some advantages. It is inexpensive (\$7 per ft^2 including labor and equipment for 45 feet of depth), and no spoils are generated, which minimizes hazardous waste exposure and disposal. Also, reactive material of up to 1-inch particle diameter can potentially be emplaced.

7.1.4 Continuous Trenching

Although not as common as backhoes or clamshells because of depth constrictions, the continuous trencher is an option for barriers 35 to 40 feet deep. It is capable of simultaneously excavating a narrow, 12- to 24-inch-wide trench and immediately refilling it with either a reactive medium and/or a continuous sheet of impermeable, high-density polyethylene (HDPE) liner. The trencher operates by cutting through soil using a chain-saw type apparatus attached to the boom of a crawler-mounted vehicle (Figure 7-6). The boom is equipped with a trench box which stabilizes the trench walls as a reactive medium is fed from an attached, overhead hopper into the trailing end of the excavated trench. The hopper contains two compartments, one of which can emplace up to gravel-size media. The other compartment is capable of simultaneously unrolling a continuous sheet of HDPE liner if desired.

The trencher can excavate in a water-filled trench without having to dewater or install sheet piles to temporarily stabilize the trench walls. Because the boom is positioned almost vertically during excavation, a trench slope is not created and greatly minimizes the amount of generated trench spoils. One other advantage is a fast production rate. At the Elizabeth City site, a reactive cell 150 feet long, 2 feet wide, and 26 feet deep was installed in one day (Schmithorst, 1996). Also, it is ideal for sites with constrained working space and minimizes soil disturbance to allow for work in sensitive areas. Drawbacks

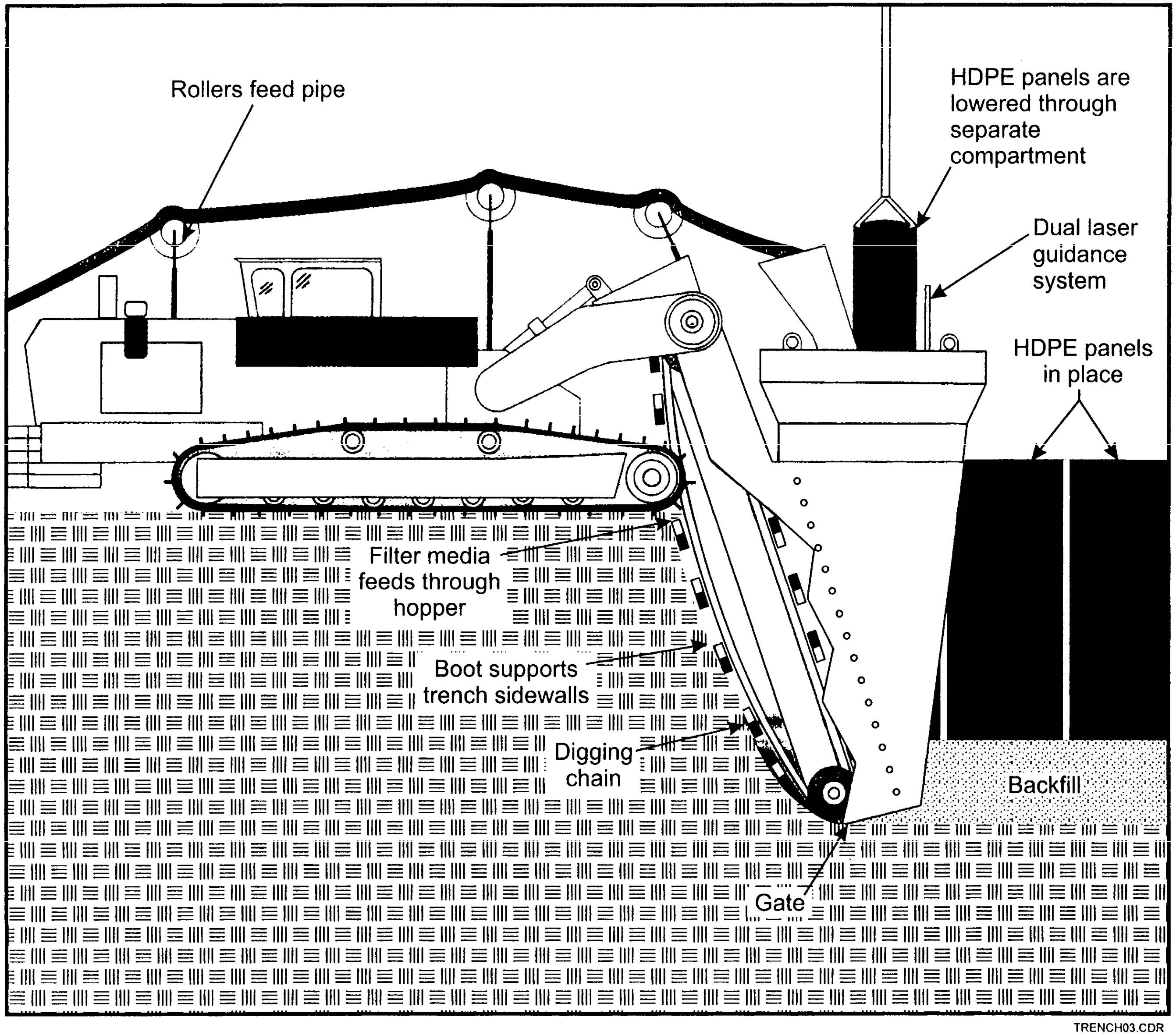
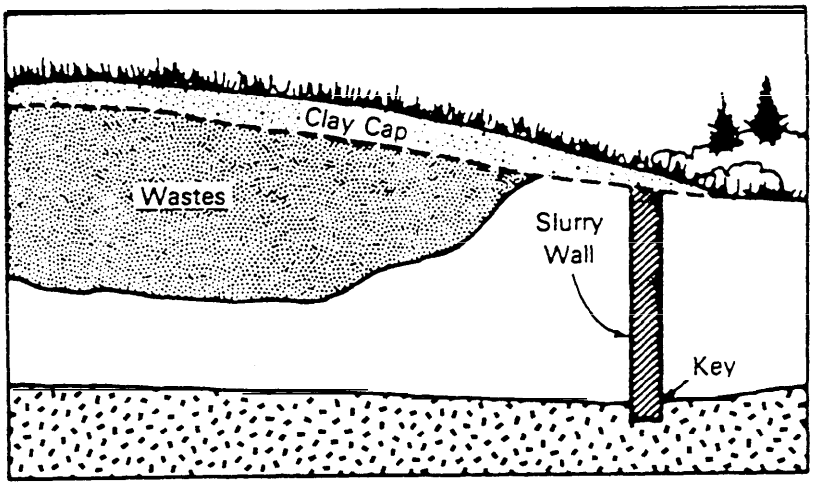


Figure 7-6. Continuous Trencher in Operation (Source: Groundwater Control, Inc., 1996)

include a shallow depth capability and problems with excavating wet, very unconsolidated materials which may cause difficulties in bringing trench spoils to the surface (Schmithorst, 1996). Obstructions such as large cobbles and boulders can also disrupt the sawing process. Quoted costs for this technique are between \$5 and \$12/ft^2 for emplacement, not including mobilization or reactive medium costs.

7.2 COMMERCIALLY AVAILABLE TECHNIQUES FOR FUNNEL WALL EMPLACEMENT

The design of some reactive cells may include flanking impermeable walls to aid in directing or funneling groundwater flow towards the permeable gate. The two most popular types of subsurface barriers are the steel sheet pile cutoff wall and the slurry trench cutoff wall. These subsurface cutoffs are either keyed in a confining layer to prevent downward groundwater migration, or less commonly, installed as a hanging wall to contain floating contaminants (Figure 7-7). If the presence or continuity of a confining layer is questionable, it is possible to install a grouted impermeable bottom barrier up to 120 feet deep.



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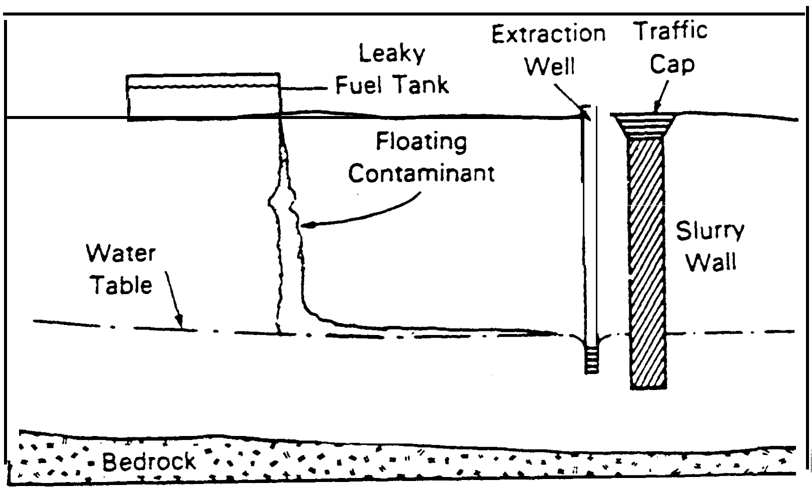


(b)

Figure 7-7. Types of Slurry Wall Emplacement. (a) Keyed-In Emplacement and (b) Hanging Wall Emplacement (Spooner et al., 1985)

7.2.1 Steel Sheet Piles

The steel sheet piling barrier is a conventional type of subsurface barrier used in geotechnical construction applications. It is commonly used as a retention wall during excavation to prevent trench collapse and to hinder groundwater flow. It is noted for its strength and integrity and will resist hydro-fracturing. The effective life range of a sheet piling wall varies between 7 and 40 years depending on the oxygen content of the soil and the corrosiveness of the contaminants (Wagner et al., 1986). Sheet piles are typically 40 feet in length but can be welded together if depths greater than 40 feet are desired. They are connected at their edge interlocks prior to being driven into the subsurface by either a drop hammer or a vibrating hammer (Figure 7-8). Sheet piles are driven in a few feet at a time along the length of the wall until they reach the desired depth. They are not feasible in very rocky soils because they are likely either to be damaged during emplacement or to meet refusal. Although sheet piles have been driven down to depths of 80 feet in the past, they begin to deviate past vertical at around 60 feet. Despite sheet pile strength and integrity, conventional steel sheet pile use in environmental applications has been limited because of the leakage that occurs through the interlocks of connecting piles.

Figure 7-8. Sheet Piles Emplaced Using a Vibrating Hammer (Courtesy of NFESC and PRC, Inc., 1996)

The University of Waterloo has developed sealable-joint sheet piling which has been used at several contaminated sites as cutoff walls. Very low permeabilities, rapid installation, and minimal site disturbance are some features of the sealable sheet pile. This special innovation features a sealable cavity in the interlocks of connecting sheet piles (Figure 7-9). After pile sheets are driven, the joint is flushed out with jetted water prior to sealing. Also, video equipment can be lowered down the cavity for visual inspection of the joint. The cavity is then sealed by grouting it from bottom to top using a tremie pipe.

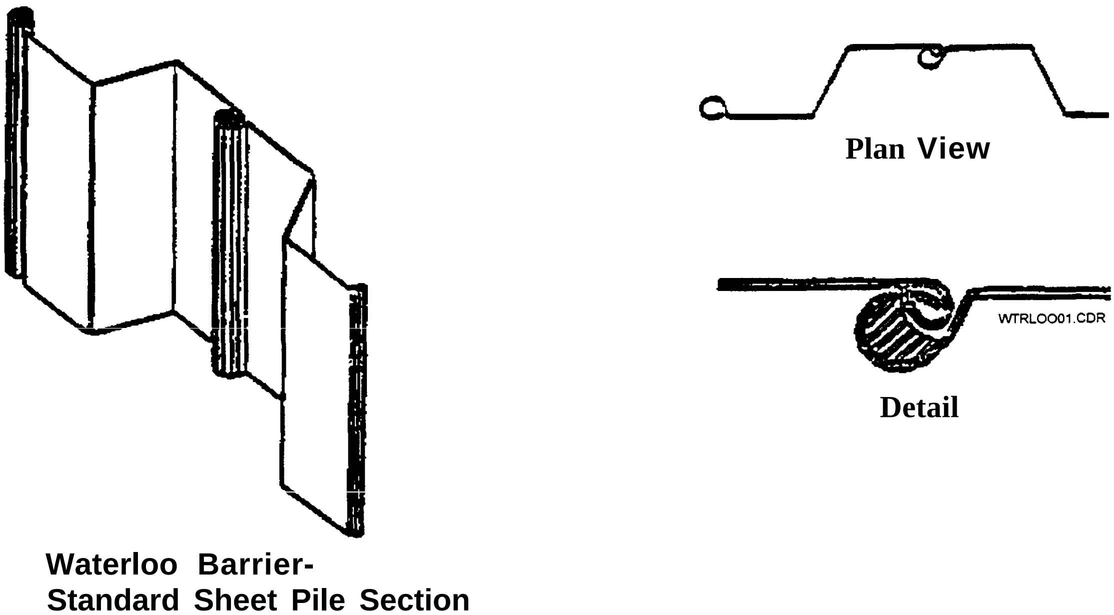


Figure 7-9. Waterloo Barrier Sheet Piles (from Smith et al., 1995)

Some uncertainties remain regarding the integrity of the joint as a sheet pile is being driven. A considerable amount of friction is produced during sheet pile installation and joint flanges could weaken or be damaged, especially if greater depths are desired (Breaux, 1996). Also, the irregular shape of the individual sheet piles and the curved nature of the interlock could create some difficulties during installation. The spaces between corrugations in the sheet piles are not accessible with clamshell excavators, and this has resulted in construction personnel entering the trench to clear away these areas (Myller, 1996). The loose interlocks of connecting piles (prior to grouting) have made it difficult to drive piles in vertically without them pinching together.

As with conventional steel sheet piles, the sealable-joint piles are limited to depths of 60 feet with confidence of maintaining sheet integrity and performance, but can be emplaced deeper. Rocky soils and consolidated/compacted sediments can damage pile sheets during installation and limit the types of geologic media through which the sheets can be safely driven. Use of sheet piles may be difficult in a funnel-and-gate system with caisson gates, although the difficulty of obtaining a proper seal between the funnel and reactive cell can be overcome through engineering modifications. The sealable-joint sheet piles currently are manufactured at only one location, in Canada, so availability could be limited.

7.2.2 Slurry Walls

Slurry walls are the most common subsurface barrier used for diverting contaminated ground-water. They are constructed by first excavating a trench under a head of liquid slurry. The slurry, which is usually a mixture of bentonite and water, helps maintain the integrity of the trench by forming a filter cake over the face of the wall. As a trench is excavated, it is quickly refilled with a mixture of cement-bentonite or a selected soil-bentonite backfill. The more common slurry walls constructed are the soil-bentonite slurry wall and the cement-bentonite slurry wall. Another, but less common, type is the plastic concrete slurry wall. All types are described in detail below.

Careful planning is critical in the design of a slurry wall. Site-specific conditions will dictate which type of slurry wall is appropriate and which is most effective. Permeability, deformability, and performance are important factors that will determine the feasibility and performance life of a slurry cutoff wall. The trench typically is excavated by either a backhoe or a clamshell, as described in Section 7.1. Although slurry walls have been used in a variety of configurations, they are especially suited for installation as a funnel-and-gate system with caisson gates because of the ease with which the seal between the slurry wall and reactive cell can be achieved.

7.2.2.1 Soil-Bentonite Slurry Wall. Slurry walls comprised of a soil-bentonite mixture are by far the most commonly used cutoff walls for environmental applications. They are the least expensive to install, have very low permeabilities, and are chemically compatible for withstanding various dissolved-phase contaminants. The construction of the wall is fairly straightforward (Figure 7-10). The bentonite slurry is introduced into the trench as soon as excavation begins. Excavated backfill can be mixed with water and bentonite. Once the trench reaches the desired depth and a sufficient length has been

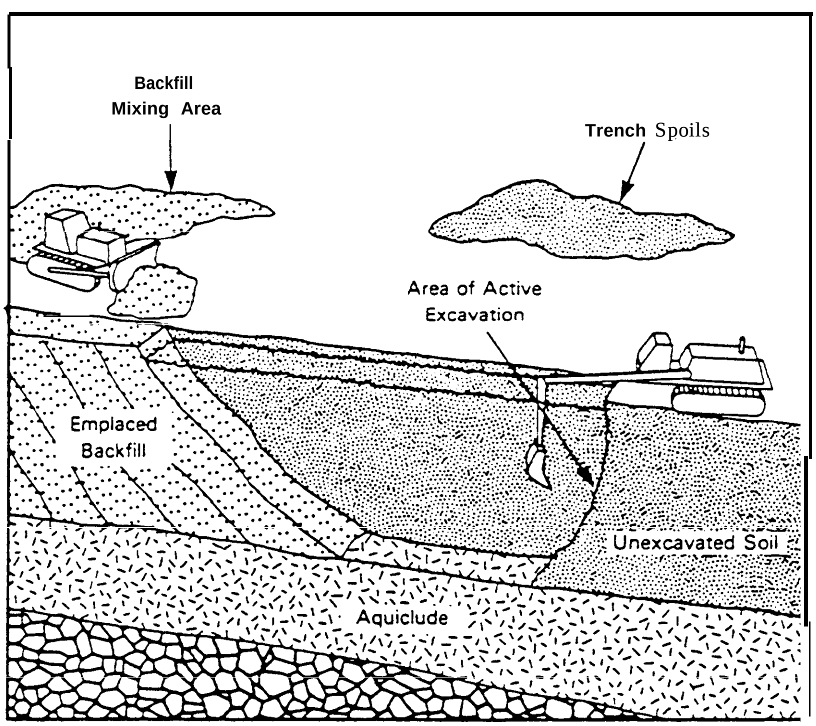


Figure 7-10. Cross-Section of a Soil-Bentonite Slurry Trench, Showing Excavation and Backfilling Operations (Spooner et al., 1985)

excavated, mixed backfill can start being pushed back into the trench. It is important to ensure that the backfill is uniformly mixed and liquid enough to flow down the trench slope. The backfill should not flow past the trench slope where it could interfere with the ongoing excavation. However, if it does not flow enough, it can start to fold over and create pockets or voids of high permeability.

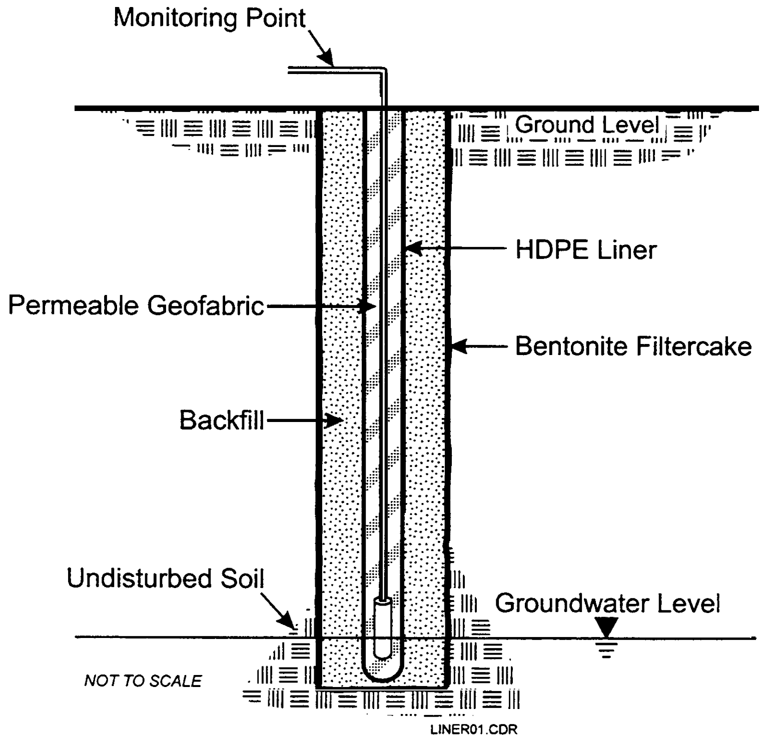
Although some factors limiting the installation of a soil-bentonite slurry wall can be overcome through careful engineering, one that cannot is space availability. It is necessary to have ample work space for adequate mixing of excavated backfill and the collection of unused trench spoils.

7.2.2.2 Cement-Bentonite Slurry Wall. Some field sites may have limited work space and not allow space for mixing the excavated backfill. Another option besides the soil-bentonite slurry wall in these scenarios is a cement-bentonite slurry wall. Construction of the wall involves excavation of a trench under a head of slurry composed of water, bentonite, and cement. Instead of backfilling the trench with mixed soil, as in the case of a soil-bentonite wall, the slurry is left to harden and will form a wall with the consistency of a stiff clay.

The use of cement-bentonite slurry walls in environmental applications is limited for various reasons. They are more expensive to install than other slurry walls because a large amount of cement is needed to fill the trench. Also, because the excavated soil is not used as backfill, it will need to be disposed of at additional cost. Moreover, because the cement-bentonite slurry wall does not contain many solids, the wall is composed mostly of water and therefore has a higher permeability and is more prone to permeation by contaminants. Advantages of the cement-bentonite slurry wall include greater strength and the ability to be installed in areas with extreme topography.

7.2.2.3 Plastic Concrete Slurry Wall. The plastic concrete slurry wall is a variation of both the soil-bentonite and cement-bentonite slurry walls. It is composed of a mixture of water, bentonite, cement, and aggregate that hardens to form a wall with significantly greater sheer strength, yet remains flexible. The plastic concrete slurry wall is constructed in paneled sections that are individually excavated under a bentonite slurry. Once a panel is excavated, the plastic concrete is poured with a tremie pipe into the panel to replace the bentonite slurry and is left to harden. The plastic concrete slurry wall is used in applications where strength and deformability are desired. It has a relatively low permeability, and based on limited data, may be more resistant to permeation by contaminants.

7.2.2.4 Composite Barrier Slurry Wall. This multiple-layer barrier offers three walls of defense, each with increasing chemical resistance and lower permeability. It is composed of an outer 1/8-inch-thick bentonite filter cake, a 1- to 2-foot-thick soil-bentonite, cement-bentonite, or plastic-concrete middle layer, and an inner 100-mil HDPE geomembrane (Figure 7-11). The HDPE has a permeability of $1x10^{-12}$ centimeters/second. Installation of the composite barrier starts with excavation of a trench under a bentonite and/or cement slurry. Because the slurry maintains trench wall stabilization, excavations greater than 100 feet are possible; however, the difficulty of emplacing the HDPE liner to those depths and the high cost of deep emplacement has resulted in restricting the use of HDPE to 50 feet (Cavalli, 1992). The geomembrane envelope is then installed vertically in sections into the slurry trench by either mounting it onto a detachable, removable frame, pulling it down using weights affixed to the membrane bottom, or “driving” it down using a pile driver. Once the HDPE is in place, the trench can be backfilled on either side of the membrane. The inside of the geomembrane then can be filled with a drainage system in which sampling points can be installed to monitor the performance of the system.



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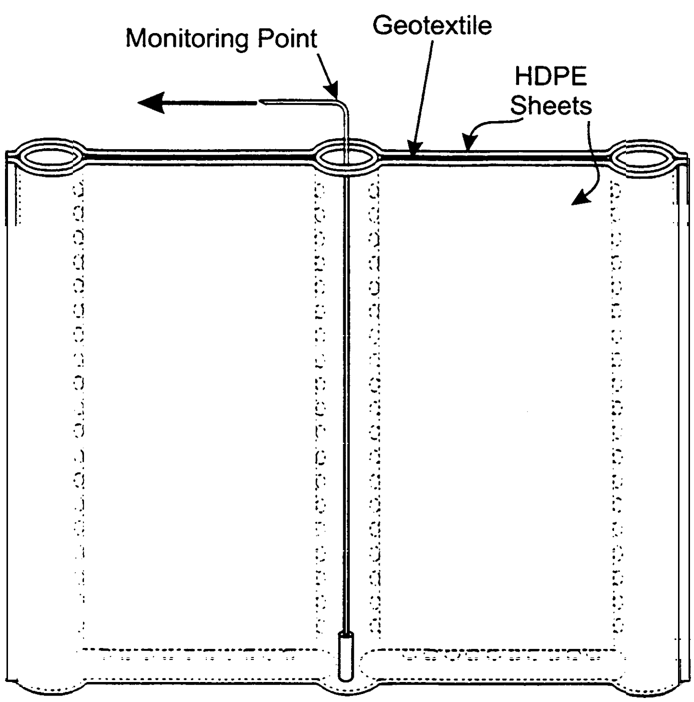

(b)

Figure 7-11. Composite Barrier Design (a) Monitoring Well Cross Section and (b) Section of HDPE Liner Envelope (after Cavalli, 1992)

Advantages of the composite barrier include a very low permeability, high resistance to degradation, option to install a monitoring system within the membrane, and ability to isolate and repair sections of the wall without removing the entire membrane envelope. Excavation of the trench is limited by the types of geologic media the particular excavator can tolerate. Backhoes, clamshells, and trenchers are successful in excavating most unconsolidated soils, but clamshells can also remove boulders, if necessary.

7.3 INNOVATIVE EMPLACEMENT TECHNIQUES

In addition to the emplacement techniques that have been used at permeable barrier sites in the past, several techniques have been used in other geotechnical applications and may merit serious consideration for permeable barriers. Because excavation equipment is not involved, these innovative techniques have considerable potential to minimize health and safety issues. However, because these techniques involve specialized equipment, they can be more expensive to operate and maintain than conventional means. Types of innovative emplacement techniques discussed include jetting, emplaced hydraulic fracturing, and deep soil mixing.

7.3.1 Jetting

Similar in many respects to deep soil mixing, jetting (jet grouting) is another innovative technique in which soilcrete columns in series form an impermeable barrier. This technique, however, involves injecting grout at high pressure through the nozzle(s) of a drill stem as it is raised up through the soil. The high-pressurized grout displaces most of the soil and can form a barrier up to depths of 130 feet. Depending on whether or not the drill stem rotates as it is raised, the resulting barrier can be either a grouted column or a thin diaphragm wall (Figure 7-12).

A systematic approach is used when injecting an impermeable funnel wall of soilcrete columns. Usually two or three rows of overlapping, interlocking columns can form an effective barrier. If three rows are desired, the two outer rows are injected first with columns emplaced in an alternating fashion. After the two outer rows are completed, the middle row of columns is injected in a similar fashion, ensuring complete contact with the columns of the outer rows.

Three variations of this method are possible depending on how many of the three jetting nozzles on the drill rods are used. A single-rod system will inject only cement-bentonite grout through one nozzle into the soil. The double-rod system uses two nozzles to inject both cement-bentonite grout and compressed air. Cement-bentonite grout, compressed air, and water are injected through three ports in the triple-rod system. The added injected pressurized air and water in the latter two methods act to cut through the soil and displace it to the surface. In the case of creating columns, all three methods will form soilcrete columns of different sizes and will displace various amounts of spoil to the surface, depending on which method is employed and the cohesiveness of the soil. Thin diaphragm walls are formed by jetting from two nozzles, creating two halves of the wall on either side of the borehole. The spoils that are generated typically are lighter, fine-grained clays and silts. Coarser sands and gravels remain to mix with the injected grout. Typically, a soilcrete column or diaphragm wall is about 50% soil and 50% grout in composition. If a soil is predominately composed of fines, most of the material will be displaced to the surface and a grout-rich barrier will be formed. Conversely, a predominately coarse-grained soil will displace less spoils and inject less grout into the soil matrix.

A single-rod system will expel a minimal amount of spoils back up the drillhole and form columns 1.3 to 4.0 feet in diameter, depending on the soil type. The cutting action of water and compressed

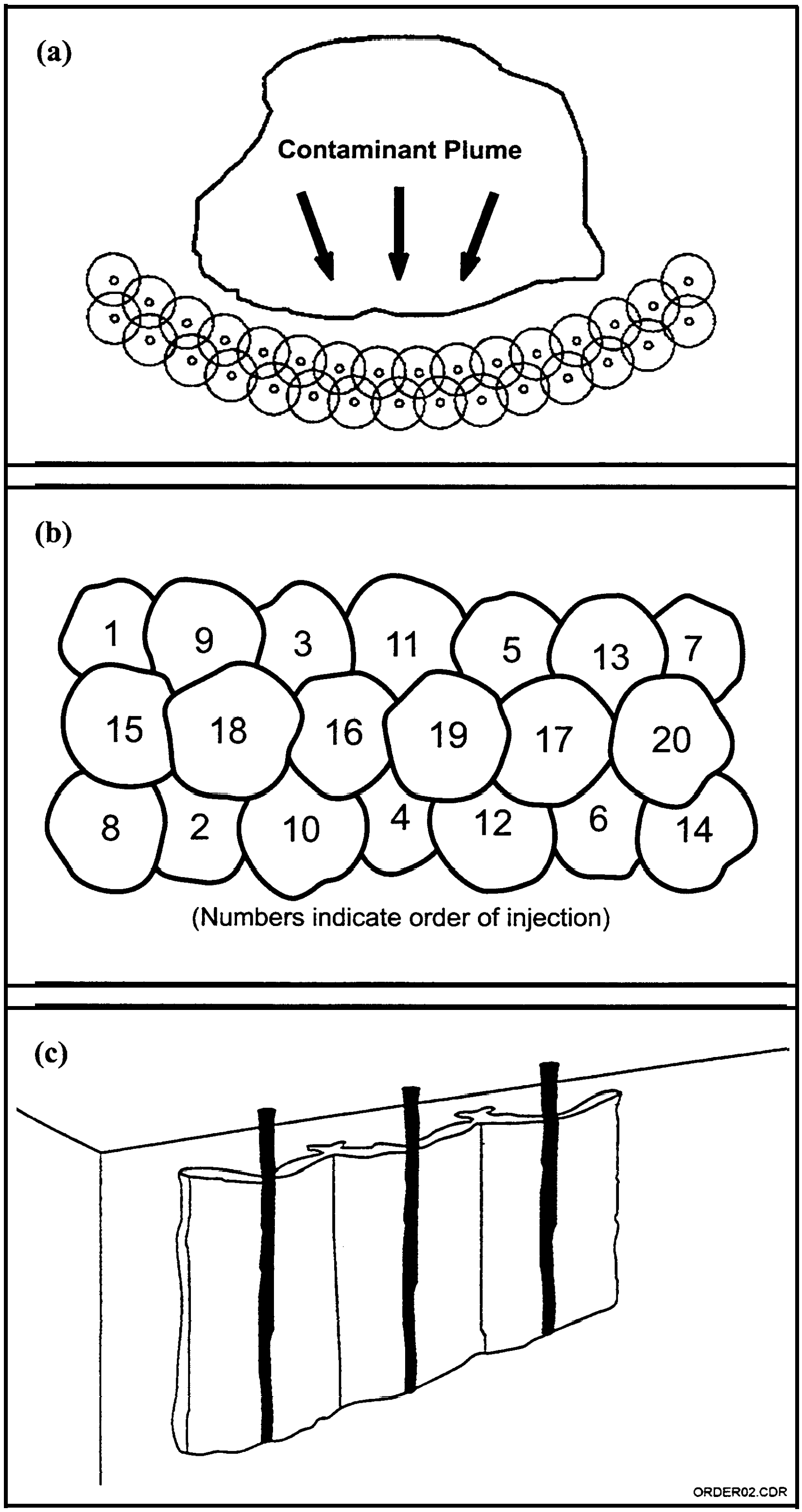

Figure 7-12. Diagram of (a) Plan View of a Grouted Impermeable Barrier (after Richardson, 1992), (b) Geometric Layout of Grouted Injection Holes (after Rumer and Ryan, 1995), and (c) Vertical Thin Diaphragm Walls (after Shoemaker et al., 1996)

air in the triple-rod system can form larger columns 1.6 to 10 feet in diameter and probably will expel more spoils to the surface. A thin diaphragm wall can range in thickness from 4 to 6 inches near the nozzle to 12 to 18 inches at the furthest extent, because the spray pattern usually is fan-shaped. The lateral extent of the wall can be from 6 to 13 feet, depending on whether multiphases or multifluids are used.

Instead of injecting pressurized grout, jetting may possibly be used to inject a reactive medium, such as granular iron, for the purpose of emplacing a reactive cell. Because the injection process expels soil fines to the surface, replacement with reactive media would increase the permeability of the column. Unless the jets are modified to inject larger particles, the reactive media, such as iron, would have to be clay-sized and be suspended in a revert (biodegradable slurry). Micropowder reactants are available and would be ideal to use, but little is known about them (Gorsky, 1996). Typical problems could be increased wear on the machinery and blocking up of pipes and hoses depending on the size of the injected media. However, injection using the triple-rod system could alleviate machinery wear because this method uses lower pumping rates. More reactive media could also be injected using the triple-rod system. Injection pumps have to be properly selected to avoid wear due to abrasive media.

7.3.2 Emplaced Hydraulic Fracturing

Hydraulic fracturing is the intentional fracturing of a subsurface formation using pumped water and air under high pressures. It has been widely used in the petroleum industry as a means to increase either the delivery or recovery of petroleum hydrocarbons from low-permeability reservoirs by creating subsurface conduits for fluid flow. The technique has recently been adopted for environmental applications as a way to emplace in situ permeable barriers. A series of horizontally stacked fractures 12 to 15 meters in diameter can form an effective reactive zone to intercept and treat downward migrating contaminants.

Hydraulic fracturing begins by slowly pumping a fracturing solution (usually composed of water and guar gum) into a sealed portion at the bottom of a cased borehole. As confining pressures are exceeded in the borehole, fractures will open and propagate out laterally from an initiation point previously notched out of the casing. A fracture-fill slurry composed of a reactive medium, such as iron powder and guar gum, can then be injected into the fracture to form a reactive treatment zone. Hydraulic fracturing generally creates fractures that are only up to 3 inches thick, so more than one fracture may be required to attain the desired residence times within the treatment zone. Some advantages to this technique include the ability to emplace a barrier to a depth greater than 80 feet. Also, fracturing causes minimal site disturbance and does not generate contaminated soils. This technique also is inexpensive. Some drawbacks of emplacement by hydraulic fracturing include the difficulty in controlling the fracture direction and the limited soil conditions in which it can be used effectively, predominantly in over-consolidated sediments.

7.3.3 Deep Soil Mixing

Impermeable barriers for funnel walls can be emplaced using specialized equipment which injects a water and bentonite slurry and/or a cement slurry directly into the soil. One such method involves deep soil mixing in which special augers in series, equipped with mixing paddles, mix up soil as they rotate. Simultaneously, a bentonite slurry is injected through a hollow drill stem as the augers retreat back to the surface (Figure 7-13). An impermeable wall is formed by successive overlapping penetrations made with the deep soil mixer, resulting in a series of hardened, “soilcrete” (grouted soil) columns. Typically, 40 to 60 percent of each soilcrete column is composed of grout.

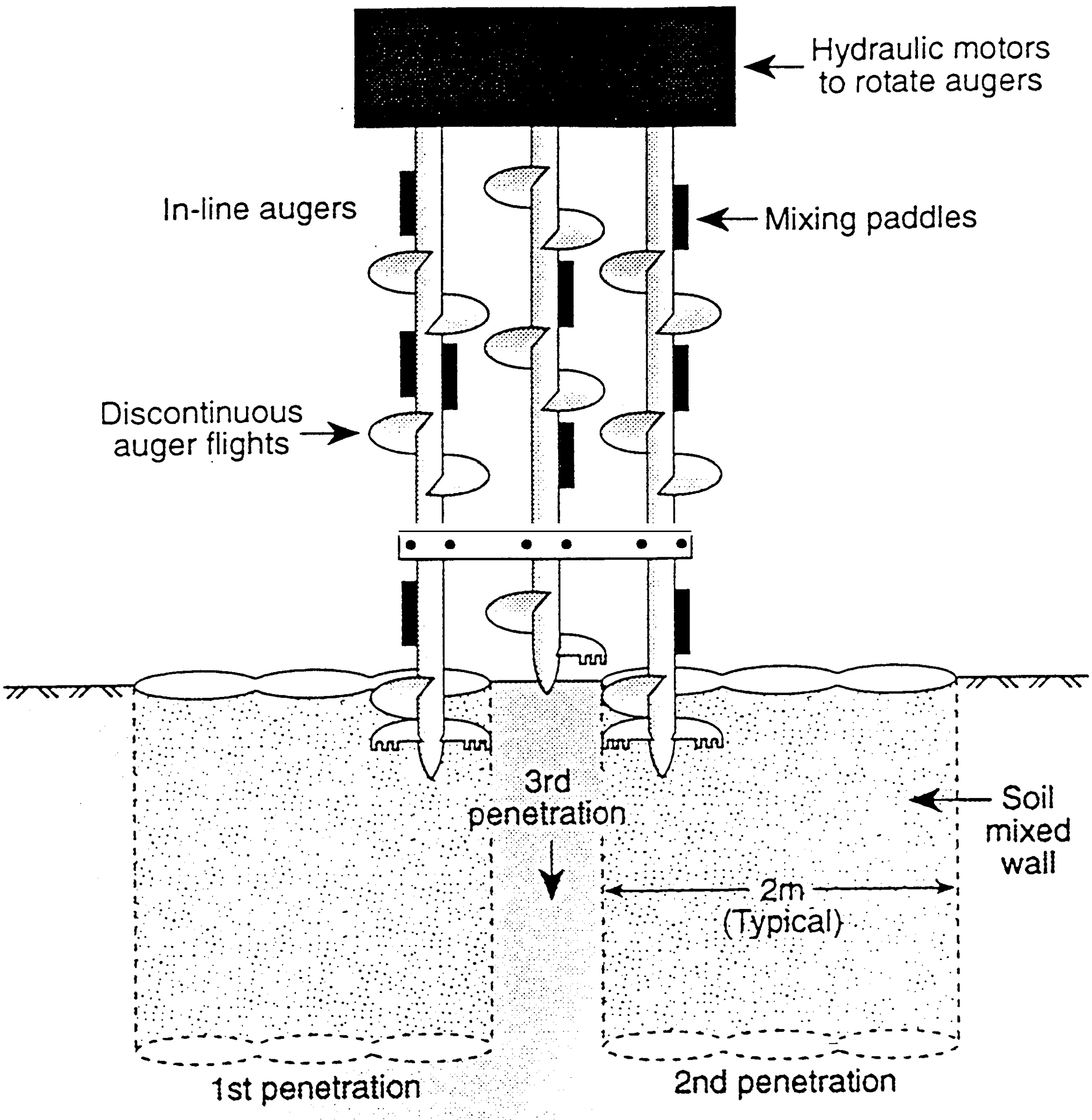

Figure 7-13. Deep Soil Mixing (Rumer and Ryan, 1995)

Depths of up to 120 feet can be obtained using this method, and permeabilities approaching 1x10^{7} centimeters/second are attainable. This method is generally employed in situations where excavation of contaminated soils is not feasible because only a minimal amount of spoils are brought to the surface. It is best used in soft soils, yet special attention should be given so that injection does not cause hydrofracturing of the soil, which can easily be done in soft soils. Generally, deep soil mixing is less expensive than jet grouting and has a higher production rate.

Although it has never been done commercially, it may be possible to utilize deep soil mixing to inject a reactive medium for the purpose of creating a reactive cell. However, because deep soil mixing does not completely replace soil with the reactive medium but rather mixes them together, only about 40 to 60 percent of the reactive medium is present in a completed column. Increased permeability occurs as the soil mixing process fluffs up the soil matrix, yet with time, compaction due to overburdening will reduce it (Burke, 1996). The injected reactant could be equivalent to fine sand-sized particles, but would have to be suspended in a revert (biodegradable slurry) to be injected. Because the slurry is injected using piston-driven cylinder pumps, several factors should be considered when deciding on the reactant particle size. The abrasiveness of the reactant can cause considerable wear and tear on the pumps, which can increase operation and maintenance costs significantly. Also, the reactant needs to be in suspension if it is to be injected in an efficient manner. One additional factor requiring consideration is the possibility of residual slurry coatings affecting the reactivity of the reactive medium (ETI, 1996).

7.4 CONSTRUCTION QUALITY CONTROL (CQC)

The effectiveness and long-term performance of either a permeable or impermeable barrier depends on the level of construction quality control that is implemented. Appendix D addresses the CQC issues involved with the barrier technologies more commonly used in environmental applications, such as slurry cutoff walls, deep soil mixing, and jet grouting. In addition, CQC issues for sealable-joint sheet piles are addressed because this technique is starting to become more widely used.

7.5 HEALTH AND SAFETY ISSUES

The success of any construction application can be attributed to prior knowledge of any foreseeable hazards and careful steps to avoid them through the implementation of safety practices under the guidelines outlined by the Occupational Safety and Health Administration (OSHA). A formal health and safety plan structured to address potential site-specific hazards will be required prior to commencement of construction activities. Listed below are a few health and safety issues that must be considered:

- Confined space entry

- Knowledge of location of existing utilities, including overhead or buried power lines, sewer lines, phone lines, and water pipes

- Types and concentrations of contaminants involved, which will dictate the type and level of personal protective equipment (PPE) required

- Use of heavy excavating equipment, requiring use of a hard hat, steel-toed boots, safety glasses, gloves, and hearing protection

- Trench entry, which may be necessary for visual inspection of important CQC issues, such as if excavation is keyed into a confining layer correctly or if buried utilities hinder use of mechanical excavation equipment

- Trench entry could be required to clear out the spaces inside the corrugations of sheet piles that are not reachable by clamshell excavators.

7.5.1 Waste Minimization

Exposure to contaminated trench spoils is likely to occur during the emplacement of a subsurface barrier. The generation of hazardous or nonhazardous waste can be minimized through careful selection of an emplacement technique that involves either no generation of contaminated spoils or generation of only minimal amounts. Sometimes design factors will dictate that a barrier be constructed in uncontaminated soil downgradient from a contaminant plume, eliminating the problem of dealing with hazardous waste. The opposite scenario could also occur, requiring excavation of soils within a contaminent plume. In any event, the amount of trenching and disposal of spoils should be planned before selecting an emplacement technique.